A THING *of* BEAUTY

Los Alamos scientists are building an instrument to probe a key frontier in nuclear and particle physics: subatomic jets of particles produced by the decay of *beauty quarks.*

 PHOTO CREDIT: Michael Pierce

Most of us don’t lie awake at night worrying about quark-gluon plasmas. Apart from infinitesimally brief blips caused by cosmic-ray collisions or manmade particle accelerators, the universe hasn’t even seen a proper quark-gluon plasma in the last 14 billion years—not since a millionth of a second into the big bang. And that one seemed to work out just fine.

But most of us aren’t Ming Liu.

A Los Alamos physicist and leader of a multi-institution team working to build a cutting-edge particle detector, Liu lives in a somewhat different mental space than the rest of us. He sees the quark-gluon plasma, or QGP—a high-temperature, high-density mixture of free quarks (which are normally bound inside protons and neutrons) and gluons (which transmit forces between quarks)—as one of only a handful of genuine research frontiers for advancing fundamental physics. It is a critical testing ground for a rare corner of particle physics that, after many decades, manages to remain relatively unconstrained by experiment. And unlike other fundamental-physics frontiers, which tend to be speculative because their effects only become evident at energies that scientists can’t achieve in a laboratory (think string theory), the QGP is—barely—accessible with current technology.

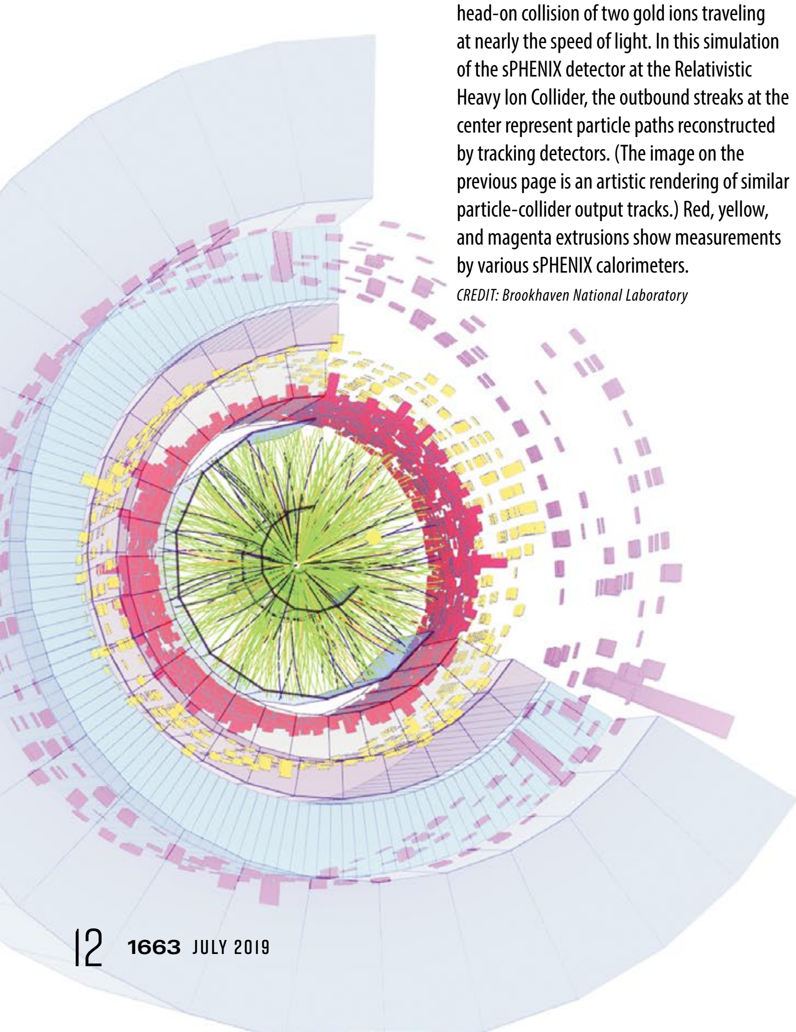
Recently, physicists at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) conducted a landmark study of the production of a particular quark, the charm quark, from within a QGP. The results were decidedly in conflict with many theoretical predictions. The charm quark's large mass should have resulted in a distinctive type of motion within the QGP, but it didn't.

Liu wonders—(is he just examining the possibilities? or perhaps grasping at straws?)—could it be that the charm quark just isn't massive enough to justify the simplifying assumptions that made the theoretical predictions calculable? The only heavier quark that could be used in its place is the bottom quark, sometimes called beauty quark or b-quark. Liu's new detector will excel at capturing evidence of beauty quarks. But will it resolve the conflict? Liu is visibly uneasy about this question.

"I'm afraid," says Liu. "I'm afraid that if this measurement goes the same way, we will have to revisit the entire picture of quark-gluon plasmas. And I don't know how we're going to do that."

Golden opportunity

On New York's Long Island lies Brookhaven National Laboratory (BNL) and RHIC, Brookhaven's signature particle accelerator. A ring-shaped particle accelerator, RHIC does what its name avers: collides heavy ions, such as the gold nuclei used in the quark-decay experiments Liu pursues, at nearly light speed. In 2005, it produced the world's first manmade QGP. Since then, only the LHC near Geneva, Switzerland, has done the same.



Simulated spray of particles produced by the head-on collision of two gold ions traveling at nearly the speed of light. In this simulation of the sPHENIX detector at the Relativistic Heavy Ion Collider, the outbound streaks at the center represent particle paths reconstructed by tracking detectors. (The image on the previous page is an artistic rendering of similar particle-collider output tracks.) Red, yellow, and magenta extrusions show measurements by various sPHENIX calorimeters.

CREDIT: Brookhaven National Laboratory

Key among RHIC's instruments that measure properties of the QGP is the Pioneering High-energy Nuclear Interaction Experiment, or PHENIX. Calling PHENIX an "instrument," however, rather undersells it; it contains a dozen detector subsystems and weighs more than 4000 tons. At one time, it engaged about 600 scientists from around the world, including Los Alamos.

In 2015, the Department of Energy decided to invest in a grand upgrade from PHENIX to super PHENIX, or sPHENIX. It is being designed and constructed by a collaboration of 77 institutions in order to probe a number of important phenomena at the forefront of experimental high-energy nuclear physics. In particular, sPHENIX will investigate jets of particles produced by the decay of free quarks; Liu and his team of staff, postdoctoral scientists, and engineers at Los Alamos are designing and building the innermost sPHENIX component that will most directly observe quark jets and, in particular, beauty-quark jets.

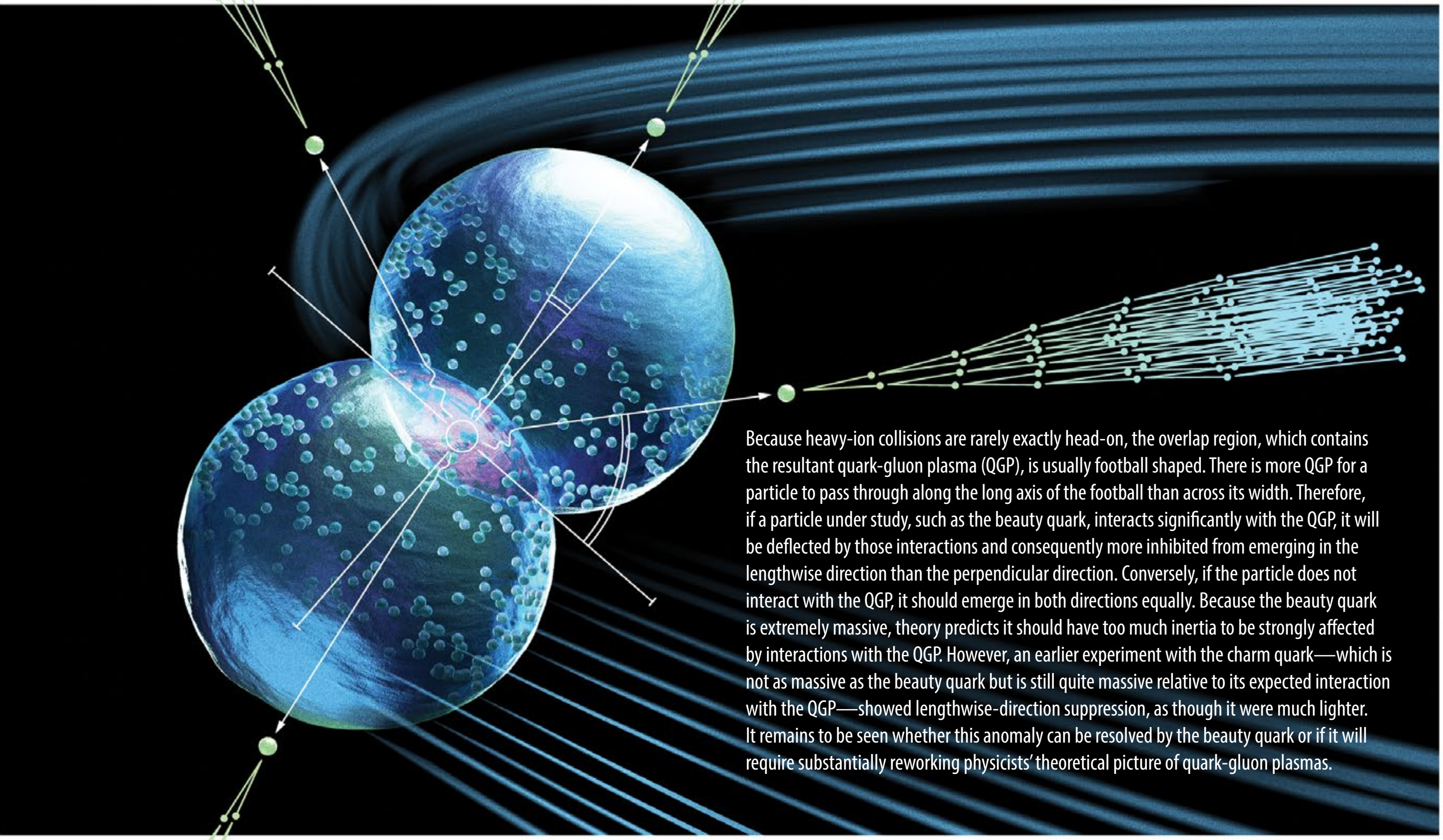
That component, by virtue of its more than 200 million tiny pixels, its exceptional time resolution, and its rapid memory-buffering capacity—all of which are tremendous leaps compared with PHENIX and other current technology—will, for the first time, allow researchers to see every one of the hundreds of particles in one of these beauty-containing jets. By gleaning information from all the jets' outgoing particles, sPHENIX will allow researchers to determine what is happening inside the QGP, similar to the way a medical scan uses various emissions to reveal what's happening inside the patient's body.

Natural flavors and colors

Much of this extravagant endeavor, like those at other accelerator facilities, is made necessary by the sheer complexity of physics at the quark level. Quarks participate in the strong nuclear force; this is the force that holds atomic nuclei together, even though nuclei are composed of only protons and neutrons. The strong force acts as a very powerful "glue" (hence the "gluons" in a QGP) that binds nuclei together despite the positive-positive electrical repulsion among the protons. But if it seems simple enough to imagine a binding force overcoming a repulsive force, the air of simplicity ends there.

While the electrical force is based on a single quantity, electrical charge, the strong force has not one but three kinds of charge, called "colors," that apply to six "flavors" of quark. Despite the everyday terminology, these colors or flavors are not things that can be understood in terms of human senses. The colors, though labeled in familiar fashion as red, green, and blue, and loosely analogous to the primary colors of light, do not in any visual sense appear red, green, or blue. The flavors—far from garlic, lemon, or chocolate—are organized into three families: "up" and "down" (the quarks from which protons and neutrons are made), "strange" and "charm," and "beauty" and "truth" (or, less poetically, "bottom" and "top"). While the antimatter partner of a proton, say, is just a negatively charged proton, the antimatter partner of a positively charged blue charm quark is a negatively charged antiblue anticharm quark.

Furthermore, while the strength of the electrical force naturally dwindles as two charged particles are moved away from each other, the strong force actually does the reverse. The energy needed to separate quarks grows as they get farther apart, until the energy is so great as to conjure more quarks into existence, right next to the original ones. (This is possible because of the matter-energy equivalence, $E = mc^2$.) In this way, the strong force generally prohibits free quarks from existing. They instead join with other quarks to make particles called hadrons (protons and neutrons are examples) because it takes an impossible amount of energy to separate the quarks. Any energy spent trying to separate atom, for instance, because hydrogen only has one electron. With the strong force, however, an attempt to probe one quark's properties will always be suppressed by charge and color screening, since extra quarks will simply appear if they weren't there already.



Because heavy-ion collisions are rarely exactly head-on, the overlap region, which contains the resultant quark-gluon plasma (QGP), is usually football shaped. There is more QGP for a particle to pass through along the long axis of the football than across its width. Therefore, if a particle under study, such as the beauty quark, interacts significantly with the QGP, it will be deflected by those interactions and consequently more inhibited from emerging in the lengthwise direction than the perpendicular direction. Conversely, if the particle does not interact with the QGP, it should emerge in both directions equally. Because the beauty quark is extremely massive, theory predicts it should have too much inertia to be strongly affected by interactions with the QGP. However, an earlier experiment with the charm quark—which is not as massive as the beauty quark but is still quite massive relative to its expected interaction with the QGP—showed lengthwise-direction suppression, as though it were much lighter. It remains to be seen whether this anomaly can be resolved by the beauty quark or if it will require substantially reworking physicists' theoretical picture of quark-gluon plasmas.

them fails either by being too little to accomplish the task or too much to prevent additional quarks from appearing and getting in the way.

The newly created quarks and antiquarks also thwart any effort to examine the properties of any quark a scientist might try to isolate. If the original quark were green, for example, the crowd of newly created quarks surrounding it would possess a mix of colors that includes a slight excess of anti-green to obscure its greenness. Something similar is true for the electrical force; the outermost electrons on an atom don't feel the full positive charge of the nucleus because of other electrons lying in between. But this charge-screening effect only happens if there are other electrons in the way. It doesn't happen at all with a hydrogen

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> *essentially a new phase of matter.*

Lost in the crowd

There are basically two things a determined physicist can do about a quark's resistance to being studied, and the sPHENIX collaboration aims to do both. The first is to seek indirect information, which sPHENIX will do by observing what happens to the beauty and antibeauty quarks created in the heavy-ion collision. Because the quarks resist being separated, they will tend to pair off into a beauty-antibeauty composite state called an upsilon particle. If that doesn't happen, however, the individual beauty and antibeauty quarks will decay separately, producing distinctive particle jets with beauty-containing hadrons. By tallying the number of upsilon particles that

With this experiment, *particle physics will get its report card.*

emerge from the collision and comparing with the number of beauty-hadron jets, scientists can infer the properties of the QGP. In particular, the hotter and denser the QGP, the more the quarks will be able to reorganize themselves to obscure one another; this screening prevents beauty and antibeauty quarks from "noticing" one another and reduces the relative number of upsilon detections in favor of beauty-hadron jets.

The other thing sPHENIX researchers can do in the face of quarks' patent shyness is just to accept that they will blend into the crowd and study the properties of the crowd instead. Because while attempting to separate quarks instigates an increasing resistance, the converse is also true: as quarks are crammed in very close to one another, the strong binding force drops away, and each quark moves around more freely. It takes an immense amount of energy to accomplish all this cramming; RHIC collides ions together at such high speed that the collision generates a temperature of 4 *trillion* degrees Celsius. (By comparison, the center of the sun is downright frigid at only about 15 *million* degrees.) But this is the essence of a QGP: a crowd of quarks so hot and dense that, paradoxically, the quarks can be expected to move about freely.

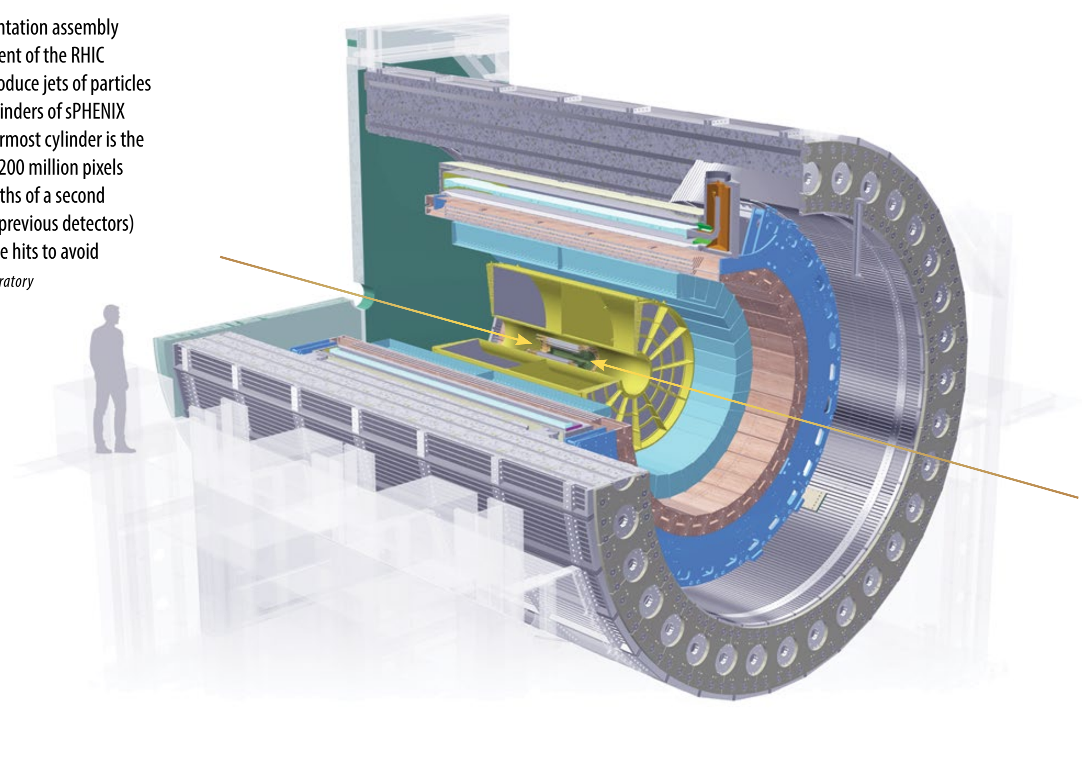
What is quark motion inside a QGP actually like? Physicists once imagined that it would be like the uncoordinated motion of air molecules, with individual particle trajectories divorced from the overall motion of the gas. However, PHENIX and the other three experiments at RHIC showed that this was untrue: the QGP was more like a liquid, with collective motion among quarks in response to pressure variations. Yet unlike everyday liquids, the QGP shows exceptionally rapid thermalization (energy sharing among particles) and almost zero viscosity (frictional resistance to flow), making it a virtually perfect liquid—essentially a new phase of matter.

PHENIX was designed to observe the QGP as the gas of freely moving quarks it was expected to be. The sPHENIX upgrade, capitalizing on new observables like beauty-containing jets and upsilon particles, will be better suited to study the QGP as the liquid-like substance it actually is.

New York jets

Like the gold ions at the Long Island accelerator lab, Ming Liu is on a collision course: a collision course with a fateful b-quark experiment using sPHENIX.

The experiment hinges on a facet of the collision geometry: The ions rarely slam into one another dead-on; sometimes they graze each other. On average, the collision overlap region is shaped like a football, like the middle part of a Venn diagram. Because the football is longer in one dimension than the others, a high-energy b-quark moving through it lengthwise will pass through more QGP than one moving across its width. If the quark is buffeted about by interactions with the QGP, then its trajectory will be somewhat deflected, with b-quarks moving in the long direction affected more than the others. The additional scatter in



Super PHENIX, or sPHENIX, is a massive instrumentation assembly more than two stories tall that surrounds a segment of the RHIC beamline. Collisions taking place at the center produce jets of particles streaming outward in all directions. The outer cylinders of sPHENIX are magnets and calorimeters; the smallest, innermost cylinder is the Los Alamos particle tracking detector. Each of its 200 million pixels will have a timing resolution of just a few millionths of a second (representing a hundred-fold improvement over previous detectors) and the ability to buffer several successive particle hits to avoid missing anything. *CREDIT: Brookhaven National Laboratory* the long direction can be quantified by keeping statistics on the outcomes of collisions. However, this length-width asymmetry would only be expected if the b-quark interacts strongly with the QGP. If the b-quark instead moves independently of the QGP and is not deflected by it, then jet production in the two directions should be equal.

One calculates the degree of interaction between the b-quark and QGP, and therefore the expected distribution of b-quark jet directions, by using quantum chromodynamics (QCD, with "chromodynamics" meaning "color dynamics"), the physical theory governing the strong nuclear force. The trouble is, even relatively simple aspects of QCD are mathematically intractable: the equations are far too complicated to solve analytically. So physicists invent perturbative approximations: they imagine a simpler, solvable system and then introduce a small perturbation intended to represent the situation at hand. Liu is working closely with several world-leading QCD theorists at Los Alamos to explore this physics. But the perturbative approximation only works if the situation at hand really is no more than a small perturbation on an otherwise solvable problem.

Liu's experiment is intended to be just that. The mass of the b-quark is much larger than that of the lighter quarks (up, down, and strange). Its equivalent mass-energy (mc^2) is also much greater than the average energy of these lighter quarks in the QGP; that is, even the kinetic energy of zipping around in a 4-trillion-degree froth pales by comparison to the mass-energy of the b-quark. Taken together, these two facts mean that the b-quark should not interact much with the QGP. It would be like a great white shark being knocked around by plankton. That's the reasoning that justifies the small-perturbation approximation: a very slight interaction between the b-quark and the otherwise plain-vanilla QGP.

The beauty of experimental physics

Will the perturbative approximation prove valid? Will the heavy quark be effectively decoupled from the sea of lighter quarks in the QGP? If so, the football-direction experiment should result in directional equality. Liu thinks it will.
Hopes it will.

Worries it won't.

"We tried a variation on this experiment with the charm quark already," Liu says. "Its mass-energy is almost ten times greater than the QGP energy. But it acted just like a light quark. It remained strongly coupled to the QGP."

The beauty quark's mass-energy is greater than the average QGP particle energy by a factor of about 40, compared to the charm quark's factor of ten. Will the extra factor of four make the difference? Will it push the experiment into a zone where perturbative QCD is valid, even though it was evidently far from valid in the previous experiment? It might. The b-quark, by virtue of its greater mass, can experience a greater separation from other quarks than a lighter quark can. It should be less strongly coupled to the surrounding QGP. But there would still be the question of why the charm quark wasn't itself decoupled. And that unexpected observation already compounds the earlier one that a QGP is more like a liquid than a gas. Taken together, one might conclude that there are already indications of new physics that differs from what is currently understood.

"I know I'm supposed to be rooting for a surprise," says Liu. "I'm supposed to say, 'I hope the beauty quark confirms the unexpected behavior of the charm quark because that will mean there's something brand new going on—a real discovery.' And part of me does feel that way. But it's daunting. It's hard to see what we're going to do if our perturbative methods go out the window."

In the high-temperature, high-density first microsecond of the big bang, everything that existed was one big QGP. Then the expansion of the universe cooled things down to the point where quarks could no longer be free and instead got bound up inside protons and neutrons. That transition between QGP and normal matter was effectively the origin of the material world. So when it comes to whether or not humanity really understands the QGP, the stakes are high.

"Therein lies both the stress and the joy of experimental physics," says Liu. "One way or another, we are going to get our answer. We are going to find out if we're wrong about all of it—quark matter, perturbative QCD, and the early universe too."

Liu's fateful view may be a healthy one. There's something to be said for those times when the stakes are high. Victory is sweetest when there's a real possibility of defeat, and very little is as instructive as defeat. So which outcome will it be?

The beauty-quark calculations will be honed. The sPHENIX instrument package will be completed and installed. And particle physics will get its report card. LDRD

—Craig Tyler

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if our perturbative methods go out the window.

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